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In turbulent shear flow the term "Coherent Structures" refers to eddies which are both spatially coherent, i.e. large eddies, and also temporally coherent i.e. they retain their identities for times which are long compared with their time scales in fixed point measurements. In certain cases, for example transitional flows, the existence of such structures is evident from flow visualisations. However in many other flows, and in the complex flows usually found in practical situations, such structures are not so evident although an evaluation of the reasons for the existence of these two classes of flows is

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first given. Attention is then focused upon the more difficult flows, particularly the round turbulent jet, where coherent structures are not so evident, and upon techniques by which the existence (or non-existence) of such structures in these flows, can be established from point measurements, backed up by flow visualisations. A major problem is shown to be the need to discriminate between real losses in eddy coherence and apparent losses in coherence introduced by phase scrambling effects which smear multipoint correlations. The analysis of multiprobe time dependent data in cold and reacting round turbulent jets is described and it is shown how evidence of strong eddy coherence can be extracted from data in spite of small values of the classical statistical cross-correlations.

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INVESTIGATIONS OF EDDY COHERENCE IN JET FLOWS

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ABSTRACT

In turbulent shear flow the term "Coherent Structures" refers to eddies which are both spatially coherent, i.e. large eddies, and also temporally coherent, i.e. they retain their identities for times which are long compared with their time scales in fixed point measurements. In certain cases, for example transitional flows, the existence of such structures is evident from flow visualisations. However in many other flows, and in the complex flows usually found in practical situations, such structures are not so evident although some indications of their possible existence have been found. In this paper an evaluation of the reasons for the existence of these two classes of flows is first given. Attention is then focused upon the more difficult flows, particularly the round turbulent jet, where coherent structures are not so evident, and upon techniques by which the existence (or non-existence) of such structures in these flows, can be established from point measurements, backed up by flow visualisations. A major problem is shown to be the need to discriminate between real losses in eddy coherence and apparent losses in coherence introduced by 'phase scrambling' effects which 'smear' multipoint correlations. The analysis of multiprobe time dependent data in cold and reacting round turbulent jets is described and it is shown how evidence of strong eddy coherence can be extracted from data in spite of small values of the classical statistical cross-correlations.

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1. INTRODUCTION

It is useful to define 'Coherent Structures' as large eddies which; (i) are repetitive in structure, (ii) remain coherent for distances downstream very much greater than their length scales, (iii) contribute greatly to properties of the turbulence; in particular, turbulent energy and shear stress, entrainment and mixing. The recent emphasis on the possibly dominating importance of the large eddies has resulted from the dramatic results of flow visualisations in certain specific types of flow, notably the two-dimensional mixing layer experiments of Roshko[1] and his co-workers.

Following these experiments it has been queried whether such large eddies were a universal feature of all turbulent shear flows. This question remains unanswered and some of the conflicting evidence is discussed briefly below. Yule[2] described how a failure to recognise and measure coherent structures in a flow by using point measurements, might be attributable to so called "phase scrambling effects". This phenomenon is also outlined below in the light of recent multiprobe data in jets. If coherent structures are indeed important features for a given flow, there arises the question of how essential it is to include descriptions of these structures in models for such flows. This problem is addressed in the final section of this paper which discusses the roles of coherent structures in jets and jet-type flows connected with turbulent combustion. This description is derived from the results of recent experimental programmes using round free jets, gaseous jet flames and turbulent liquid fuel sprays.

2. THE RECOGNITION OF COHERENT STRUCTURES

One can conveniently divide experimental turbulent flows into those in which coherent large eddies have been unambiguously identified, both in flow visualisations and point measurements (Class 1), and those in which such eddies are not so immediately obvious (Class II). The questions arise:

(i) Are the Class I flows, or the experiments which investigated them, 'pathological'* in the sense that special peculiarities introduce or enhance such structures?

(ii) Are coherent structures in fact present in all, or some of the Class II flows but these are not immediately identifiable due to various obscuring phenomena?

These questions should be answered before the phenomenon of coherent structures is included in physical models for turbulence. The present experimental evidence is so incomplete, and often contradictory, that it is not possible to give firm answers to either question; even when one considers a narrow class of flow such as the plane mixing layer which has recently been subjected to many investigations. However below a checklist is given, of phenomena which may contribute either to the

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* 'Pathology' is here used with its meaning; 'the study of abnormalities'

pathological nature of an investigation or to obscuration of coherent structures. Reference is made only to jet and mixing layer flows although the general comments apply also to other turbulent shear flows.

2.1 Contributions to the possible 'Pathological' Nature of Experiments

Turbulent or Transitional Flow?

Fully developed turbulent flow is recognised from point measurements by: -

(i) Three-dimensionality, so that u, v, and w fluctuations are of the same order. This requires that the larger eddies (which contain most of the turbulence energy) cannot be completely two-dimensional. This does not however prohibit these eddies from being coherent in the azimuthal, or spanwise, sense while for example, having 'wrinkles' along their lengths.

(ii) A wide and continuous frequency or wavenumber, spectrum without sharp peaks and harmonics. (For this situation the 'energy cascade' process is generally accepted to exist).

For jet and mixing layer flows the problem of defining the distance downstream required for fully developed turbulence to be established remains unresolved. As sketched in Fig. 1, the transition process is complex, involving an inviscid initial instability mechanism whilst viscosity influences the rolling-up of the mixing layer into vortices, and also influences the core sizes of these rings and thus the mode of the subsequent three-dimensional instability.[3] The coalescing of the transitional vortices is basically an inviscid process but viscosity can again have a stabilising influence.

It is certain that the large eddies in transitional flow are both highly coherent and also 'two-dimensional'. It is thus necessary to ensure that a flow is locally fully turbulent before studying the local eddy structure. The only method of ensuring this is by making sufficient local point fluctuating velocity measurements to check that the flow satisfies the above criteria; Measurements of mean velocity distributions and spreading rate are not sufficient.

Another aspect of turbulent flow is the existence of a random small scale turbulence structure which ensures rapid mixing once fluid has been entrained into the turbulent flow (by the large scale structure). Some plane mixing layer experiments[4] show that this small scale structure can be established when the large eddies are still two-dimensional. It thus appears that all of the various attributes of fully turbulent flow need not be established at the same positions downstream.

Pressure Field and Rig Effects

There are many examples of experiments in which the rig dimensions strongly influence the turbulence structure in an unexpected and unwanted manner. For example acoustic feedback is well known in compressible

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and combustion flows. Bradshaw[5] has proposed that even for incompressible flow, the plane mixing layer, and particularly the irrotational velocity field outside it, can be strongly influenced by the test section floor significantly before the attachment position. It has also been suggested that wall and floor effects may enhance the spanwise coherence of the irrotational flow, while the turbulent flow may not be particularly coherent. Going even further, others have suggested that the spanwise coherence of the turbulent eddies themselves, is enhanced or prolonged by the pressure fields introduced by rig effects. Unfortunately these proposals remain unresolved either way. The typical plane mixing layer experiment can have up to four rig length scales: Heights of the initial primary and secondary flows. Width of test section. Length of test section. When the characteristics of the splitter plate boundary layers, the test section boundary layers and the initial turbulence characteristics are also considered, it is not surprising (in hindsight) that observations made using different rigs do not always agree. However the various experimenters have proposed their flows to be fully developed and Bradshaw has raised the question whether the mixing layer can have two self-preserving forms; with and without two-dimensional large eddies.

It might be considered that the plane mixing layer is a relatively 'simple' turbulent flow which is an ideal candidate for experiments designed to gain insight into the physical structure of the turbulence. Unfortunately this has not proved to be the case due to the unresolved problems described above. There is thus a strong case for the study of the round free jet, in spite of its undoubtedly more complex flow field. With properly designed nozzle and settling chamber, the round free jet does not suffer from rig effect. A large body of 'classical' data is in existence and the jet is closer in character to the flows which exist in more practical mixing systems.

The Effects of 'Forcing' the Flow

In many jet-type flows experiments have been carried out by using a periodic 'forcing' of the jet; using sound fields, pressure fields or sparks. Once can broadly divide these experiments into those which have the objective of measuring the effects on the turbulence structure of the forcing and those which have the intention of making coherent structures more amenable to measurement. These latter experiments have problems in their methodology and interpretation. In particular it is assumed, at least implicitly, that the turbulence structure is basically similar with and without forcing and that the eddies are merely made more easily measured. However in practice it is found that the jet can be drastically changed by forcing, with differences found in the velocity profiles, rates of spread, turbulence intensity, shear stress etc. It therefore does not seem to be reasonable to deduce information regarding 'natural' turbulence by studying such forced jets. One can propose, on the basis of the available evidence, that a result of forcing the jet is to prolong the existence of the relatively orderly transitional flow, perhaps by delaying the onset of three-dimensionality in the large eddies. One can also surmise that an essential feature of

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of the 'real'turbulent flow is the natural dispersion of the strengths, wave numbers, separations and trajectories of eddies as they move downstream. Forcing can delay the dispersion and thus delay 'real' turbulence.

2.2 Possible Contributions to Difficulties in Observing Coherent Structures

Yule[2] described how the so-called phase scrambling effects can make the recognition of coherent structures from point measurements very difficult. In a typical conditional sampling experiment structures are sampled and ensemble averaged at times measured relative to trigger events. As indicated in Fig. 2, quite small variations in the structures and their positions at the time of sampling, can cause large changes in the signals which they produce. This can cause the signals received by the conditioning sampling technique to be quite small in amplitude, although the actual signal amplitudes corresponding to individual eddies can be maintained. Thus conditional sampling experiments should indicate the approximate average structures of eddies but they are not necessarily reliable for indicating the coherence of eddies nor for showing details of the eddies. On the other hand if coherent structures are present some indication at least of their presence should be found in signal time histories, conditionally sampled signals and cross-correlations.

Flow visualisation of coherent structures is often difficult in fully turbulent jet flow because of: (i) the three-dimensional structure of the turbulence, (ii) the rapid diffusion of marker species by the small scale turbulence and (iii) an outer 'sheath' of small scale turbulence which can obscure the main motion inside the jet. In spite of this, indications of these eddies can be seen in schlieren photographs. In particular the potential flow entrainment regions between eddies can be seen, even though the eddies themselves are not as clear as those seen in visualisations of transitional flow. Slit lighting can also improve the visualisation of the large eddies, but it remains true that visualisations of the eddies in the turbulent regions of round jets have never approached the clarity of the plane mixing layer visualisations of Roshko et al.

3. Structure of Cold Jets

Figure 1 shows the structure of a jet developing from a laminar nozzle boundary layer, drawn on the basis of numerous flow visualisations. The general flow structure is qualitatively the same for a wide range of Reynolds numbers ($3000 < Re < 2 \times 10^5$). The laminar mixing layer rolls up periodically into vortex rings. These coalesce and sometimes coalescence can occur several times. Azimuthal core waves develop until the distorted vortex rings coalesce and turbulent large eddies are formed.

It is important to discriminate between the transitional and turbulent flow regions. Fig. 3 shows spectra along the inside edge of the mixing

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layer inside the potential core for a 50.8 mm diameter jet with $Re = 2.1 \times 10^4$. The appearance of subharmonics is a characteristic of the transition region and this indicates that the vortices coalesce fairly consistently at given positions. The jet represented by Fig.3 has three distinct coalescing regions; the fundamental frequency occurs very close to the nozzle and it has a Strouhal number

$$St_D = fD/U_j \approx 4.2$$

and this is not shown in the plotted spectra. Other jets are found to have two or only one clear coalescing regions in the transitional flow. For example Fig. 4 shows spectra in the potential core of a 25.4 mm diameter jet with Re = 10,500. Figure 5 shows the spectra in the centre of the mixing layer of the same jet and here, although the fundamental and subharmonic frequencies agree with the potential core values, there are also higher harmonics present. These are caused by modifications to the basic cosine-type signal which result from the cores of the vortices passing the hot wires. Numerous experiments [3, 6, 7, 8] have shown that the peak frequency f_p corresponding to the natural shear layer instability agrees well with the most amplified frequency predicted by Michalke[9] so that

$$St_\delta \equiv f_p \, \delta_j / U_j \approx 0.07$$

for the typical experimental range of δ_j / D : $0.001 \leq \delta_j/D \leq 0.01$.

Here δ_j is the laminar nozzle boundary layer shear thickness,

$$\delta_j \equiv - U_j \, (\partial U / \partial r)^{-1}_{max}$$

Yule [3] proposed that the transitional round jet mixing layer can be assumed to end where all three fluctuating velocity components have reached similar, nearly asymptotic values and this coincides approximately with the attainment of turbulent forms for correlations and spectra. Fig. 6 shows measurements of

$$(\bar{v}^2)^{1/2} \quad \text{and} \quad (\bar{w}^2)^{1/2}$$

along the centre of the mixing layer for different jets. It is interesting to note the gradual increase in w fluctuations in the transition region and this corresponds to the gradual growth of waves in the vortex cores. By using this type of data the transition distance x_T can be estimated for various jets and the results are given in Fig.7 Bradshaw suggested the proportionality

$x_T \approx 1000 \; \theta_j$ where θ_j is the nozzle boundary layer momentum thickness. This gives $x_T \approx 250 \; \delta_j$ and this is seen to give a fair approximation to the data for most of the range.

The initial instability frequency given by Michalke's theory is a weak function of δ_j / D so that

$$f_p \, \delta_j / U_j \approx 0.07$$

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The subharmonic and quarter-harmonic peaks approximately (but not exactly) halve each time during coalescing. One would expect some correlation of the various data on peak frequencies in jets when plotted in the form

$$f_p \delta_j / U_j \quad \text{against} \quad x/\delta_j$$

Available data are plotted in Fig. 8 which shows measured frequencies corresponding to the fundamental and the various lower harmonics. There is seen to be a reasonable collapse of the data when plotted in this form.

Thus the transitional jet is relatively orderly and is amenable to conditional sampling studies. A typical arrangement for conditional sampling is shown in Fig. 9. Signals from recovery probes are ensemble averaged at times measured relative to events located in the signal from the trigger probe. Bruun[10] has used this technique in a jet transition region to educe the averaged velocity fields of coalescing vortex pairs. As shown by Fig. 10, the proportion of the signal recovered by this technique was very high in the transitional jet and this indicates the repetitiveness of the vortices and their movements.

When one moves downstream into the turbulent region (i.e. either the turbulent mixing layer or the turbulent fully developed downstream regions) the situation becomes much more difficult with regard to the application and interpretation of conditional sampling experiments. A useful technique for relating observed structures to point signals, is to film the flow at the same time as probe signals are recorded. Figure 11 shows the signals accompanying the passing of a typical large eddy, as delineated by dye patterns in a submerged water jet. It is found that -ve potential core 'u' peaks occur after the eddy has passed, strong -ve peaks (or 'spikes') are distinctive of the region inside the eddy.

By using, for example, the -ve spikes in the inner side of the mixing layer as triggers one might hope to educe the average eddy structures. In fact the ensemble averaged signals[11] which result at the recovery probes are then of low amplitude and thus are barely comparable, in their information content, with the corresponding cross-correlations. For example Fig. 12 shows the peak amplitudes of recovered signals in the turbulent jet as a proportion of the local r.m.s. signal. It is seen that the amplitude of the recovered signal falls very quickly with increasing distance from the trigger position, in comparison with the conditional sampling results in the transitional flow. This lack of recovered signal must be connected with the relative difficulty of visualising the eddies in the turbulent region compared with the transitional region.

As has been pointed out[2] an objective of future conditional sampling experiments must be to discover how much of this loss in amplitude can be attributed to the various phase scrambling effects of basically repetitive coherent eddies, and how much represents a real loss in

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amplitude caused by a loss in coherence (break down) of the sampled eddies. This question is unresolved quantitatively, however, the indications of several flow visualisations[3,7] are that the sampled eddies do remain coherent for very considerable distances downstream.

A major contribution to the smearing or scrambling of signals comes from the growth of three-dimensionality in the large eddies. This can be seen in Fig. 6 and also in cross correlations with probes separated by π, in the centre of the mixing layer, as shown in Fig. 13. It can be seen that the growth of w fluctuations along the jet in the transition region is accompanied by a loss of circumferential cross-correlation. However it remains unclear whether this results from a true loss of circumferential coherence of the transitional vortices (so that the turbulent large eddies are perhaps rather similar to the horseshoe vortices found in boundary layers) or alternatively the turbulent eddies are circumferentially coherent but have an azimuthal 'lobed' structure which is smeared out by phase scrambling effects. Front views of the turbulent jet using transverse slit lighting give no clear indication of circumferential coherence, but certain flow visualisations do give an impression of this and a helical turbulent eddy structure has even been proposed for certain flows (see Section 4 below).

By using very large -ve potential core u fluctuations as trigger signals Yule[3] found that a certain class of turbulent large eddy could be educed. There is considerable evidence that the inner side of the turbulent round jet mixing layer contains eddies which either retain their coherence longer than in the central and outer part of the mixing layer, or are more repetitive in their structures and movements. This can be seen in the contours of recovered signal amplitude in Fig. 12. By sampling particular examples of these inner eddies which are unusually close to the centre of the jet, the phase scrambling effects are reduced and substantial values of educed signals can be recovered downstream of the trigger probe. For example, Fig. 14 shows recovered u and v time histories at $x/D = 2.5$ for triggering at $x/D = 2$, $r/D = 0.1$. It is interesting to note that recovered u signals are small at the outer part of the mixing layer ($\eta > 0$) but the recovered v signal is significant for the complete width of the mixing layer. This is common to all conditional sampling experiments in round jets which show a much greater spatial coherence for the transverse velocity component than for the other velocity components. To some extent, at least, this might be attributed to the smearing effects of the differing convection velocities from one eddy to the next. However examination of Fig. 14 shows that, although the magnitudes of the educed u and v signals are large, there is nowhere within the turbulent mixing layer where the peaks of these sampled signals, are in phase. If one repeats this sampling procedure, but with the trigger probe at the centre of the mixing layer, one finds a rapid decrease of educed signal amplitude with increasing probe separation, but u and v are, on average, in phase in the central part of the mixing layer.

Thus although the sampled structures contribute greatly to the turbulence intensity, they are not by themselves the main shear containing feature of the turbulence. The averaged velocity field of these sampled inner eddies is shown in Fig. 15. They are seen to be similar to vortex

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rings in cross section. It is considered that these eddies interact with the structures at the outer part of the flow which are not being detected by the triggering criterion used. This interaction produces the shear containing uv 'spikes' inside the mixing layer.

The potential core fluctuations, adjacent to the turbulent mixing layer, do not exhibit the subharmonics found near the transitional region. However, a single clear frequency peak is found near the turbulent region, which indicates a strong periodicity of the inner turbulent eddies. The frequency of the peak gradually reduces in value[3] with increasing downstream distance. This indicates that the inner turbulent eddies have a high degree of randomness in their motions.

4. DISCUSSION : COMBUSTION FLOWS WITH COHERENT STRUCTURES

Experiments with burning round jets of pure gaseous fuel (propane), and various fuel/air mixtures, have been carried out in Sheffield[12, 13, 14]. As in the cold jet experiments described above, the gas jet is carefully designed to have a uniform velocity profile at the nozzle, with a turbulence level less than 0.5% and a laminar nozzle boundary layer. Many of the features found in cold jets are found in these 'jet flames' although there are, quantitatively, significant modifications. Figures 16 and 17 sketch the typical appearance of the jet flame near the nozzle and further downstream. Two distinct vortex-like instabilities are seen. An inner high velocity, high frequency instability appears to be driven by combustion process, whilst an outer, slower moving instability appears to correspond to the vortex rings resulting from the Kelvin Helmholtz instability similar to the cold jet. Reaction occurs in interface layers, which are distorted by the vortices and provide clear visualisations of these vortices in schlieren films. A laser schlieren technique measures the deflections of a 1 mm laser beam passing diametrically through the flame. The technique is sensitive to any high temperature zones which are circumferentially coherent. Figure 18 shows the spectra obtained by using this technique at different distances along the centre of the mixing layer of the flame. Discrete peaks are found in the spectra and there is a transfer of energy to lower frequencies, but unlike the cold jet, subharmonics do not clearly appear with increasing distance downstream. In fact the laser schlieren peaks correspond to the high frequency eddies found at the inside of the jet flame mixing layer. These peak frequencies are compared with the average passing frequencies of the inner eddies measured from high speed schlieren films, in Fig. 19. Although it provides mean velocity and turbulence level data, Laser anemometry is not a useful technique for point measurements of the frequency spectra of velocity in flames, because of the restrictions introduced by the need to seed the flow. Ionisation probes[14] have a good frequency response up to several kH_z and these are sensitive to the local occurrence of reaction. These probes are found to be sensitive to both the inner and the outer eddies and spectra are produced (Fig. 20) which are similar to those measured by hot wires in cold jets. Examination of spectra such as these shows that the transition distance x_T is typically 3 to 5 times longer in a jet flame than in a cold jet with the same exit velocity. L.D.A. measurements[12]

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show that the jet potential core can lengthen by a factor of 5 for the flame case.

Similar to the use of hot wires in cold jets, two ionisation probe signals can be cross-correlated with variation in probe separation and time delay. Figure 21 shows the cross-correlations from two probes with varying streamwise separation. It is seen that both the slow convection of the outer eddies, and the fast convection of the inner eddies are detected by this technique (the first small 'kink' in the cross-correlations is produced by the inner eddies).

The transitional jet flame, like the transitional cold jet, is relatively orderly compared with the turbulent flame region and is thus amenable to investigation. Processes such as the growth of the azimuthal core waves and coalescence can also be seen in the transitional flame. Large eddies can also be seen in the turbulent region of the jet flames, and it has been observed that certain individual eddies can be seen to exist for almost the full length of visible flame (100 D). Sections of reacting interface have been identified [13] from their formation near the nozzle to at least 20 D downstream. The large eddies, their structures and their coherence, have important repercussions with respect to mixing, reaction and pollutant formation. In line with suggestions by Yule[2] multiple probes are being used in order to attempt to track individual eddies as they move downstream.

In this way the existence times and retention of coherence of individual eddies can be examined and the smearing of cross-correlations by jitter can be quantified.

As an example Fig. 22 shows simultaneous time histories from 8 miniature thermocouples separated in the x (streamwise) direction by intervals of 1.5 D, with the probe nearest the nozzle at x = 4D. The probes are near the centre of the mixing layer, at r = 0.63D. It should be noted that the jet mixing layer region (i.e. where a potential core is found), can stretch beyond x ≐ 15D for the flame case.

Temperature time histories from the same longitudinal probe array are shown in Fig. 23 for the case r = 0.71D, i.e. with the probes slightly nearer to the low velocity side of the mixing layer. In addition Fig. 24 shows the space-time cross correlations between the probe at x = 4D and each of the other probes, for the case r = 0.63D.

Examination of Figs. 22, 23 and 24 illustrates several of the phenomena which have been discussed, concerning eddy coherence and the obscuration of coherence in statistically averaged data. Figure 22 shows that most eddies (as marked by temperature peaks) can be tracked individually, from probe to probe, between x = 4D and x = 14.5D. However as shown by Fig. 24, the cross-correlation between signals at these two positions is small in amplitude. Variation in the convection times, from eddy to eddy, gives a contribution to this smearing. However a further important contribution arises from variations, from eddy to eddy, in their radial (and perhaps azimuthal) movements so that a probe 'sees' a different part of each eddy. This is particularly clear nearer the nozzle in Fig. 23.. It is considered that the the double-peaked structure

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of eddies found near the nozzle (e.g. x = 4D in Fig. 23) may be indicative of a hot reacting region wrapped around a relatively cool eddy core. The signals at x = 4D and x = 5.5D in Fig. 23 clearly demonstrate how the relative magnitudes of these double peaks vary from eddy to eddy, presumably because of radial variations in eddy positions. An interesting phenomenon is the almost complete disappearance of indications of some eddies at certain times and positions, but the subsequent reappearance of these eddies at probes further downstream. This can be seen in Fig. 23 at the end of the time history for x = 7D.

Multiprobe experiments of this kind show that a one-dimensional probe array gives indications of the existence of eddy coherence and also indicates the smearing, or phase scrambling effects. However two-dimensional arrays may be required to more clearly elucidate and quantify these effects.

In conclusion two examples will be given of the necessity for understanding coherent structures if satisfactory models are to be developed for turbulent combustion flows. Considering firstly the case of two phase flow, such as a turbulent liquid fuel/air spray, considerable photographic evidence has now been gathered in the author's laboratory showing that coherent large eddy structures play an important role in the dispersion, mixing, vaporisation and burning of sprays. Small droplets closely follow the gas flow and give a good visualisation of the large eddies. However, larger droplets with their smaller drag/inertia ratios, can be seen to leave these eddies and penetrate the outer potential flow. Realistic modelling of droplet environments and thus vaporisation and burning, requires modelling of the large eddies and their interactions with the droplets. The second case concerns the field of pollution modelling and control. The existence of eddies, or of reacting interface layers, for distances comparable with the total flame length should have important repercussions on the production of pollutants such as soot and NO_x. One can envisage flows in which eddies may be considered as reactors which are continually entraining, mixing and burning air, fuel and products. Current modelling approaches, based on time average flux equations, should preferably be adapted to include information derived from knowledge of the spatial fields within these eddies and also their time histories. A major objective of future research must be the development of techniques for including this 'Lagrangian' coherent structure information within computer models in a computable, yet physically meaningful, manner.

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Figure 1 Physical structure of transitional jet.

Figure 2 Different modes of jitter, and their effects on signals.

Figure 3 Spectra of u in 50.8 mm diameter cold jet at $\eta = 0.15$ for $Re = 2.1 \times 10^4$

Figure 4 Spectra of u in 25.4 mm diameter cold jet $r = 0$ $Re = 1.05 \times 10^4$

Figure 5 Spectra of u in 25.4 mm diameter cold jet $r = 0.5D$, $Re = 1.05 \times 10^4$

Figure 6 Longitudinal distributions of turbulence intensity at $r = 0.5D$, ••——•• $Re = 9 \times 10^3$, ———— Re = 3.5 x 1C •——•——• $Re = 5 \times 10^4$, -------- $Re = 10^5$.

Figure 7 Jet transition distances as a function of nozzle boundary layer shear thickness. ▲ Yule 25.4mm dia. jet, ● Yule 50.8mm dia. jet, O from data of Bradshaw[6]

Figure 8 Measured vortex frequencies versus distance downstream in transitional jets, air and water, various Re and diameters. (Refs 3, 8, 11, 13)

Figure 9 Conditional sampling in the mixing layer of a round jet.

Figure 10 Percentage of local rms signal recovered by ensemble averaging eddies in round jet, $Re = 10^4$

Figure 11 Time histories of velocity measured by probe array and injected dye pattern in turbulent water jet.

Figure 12 Percentage of local rms signal recovered by ensemble averaging eddies in turbulent jet, $Re = 2 \times 10^5$

Figure 13 Cross-correlation of u at diametrically opposite sides of jet at $r = 0.5D$.

••——••——•• $Re = 9 \times 10^3$, ———— $Re = 3.5 \times 10$

Figure 14 Conditionally sampled time histories of u and v at $x/D = 2.5$, $Re = 4.3 \times 10^4$, Triggered by large negative u peaks at $x/D = 2$, $\eta = -0.2$

———— u_s , – – – – – v_s

Figure 15 Conditionally sampled velocity field associated with large negative u peaks at $\eta = -0.2$, $x/D = 2$, $Re = 4.3 \times 10^4$

Figures 16 & 17 Sketches of structures of jet flame taken from schlieren films, $0 \leq x/D \leq 5$ and $10 \leq x/D \leq 15$ respectively. $Re = 1.05 \times 10^4$. equivalence ratio = 10.4

Figure 18 Spectra of density gradient fluctuations measured by laser beam deflections (laser schlieren) in jet flame, $Re = 1.05 \times 10$ equivalence ratio = 10.4

Figure 19 Comparison of laser schlieren spectra peaks with eddy passing frequencies measured from cine films,in jet flame.

Figure 20 Power spectra of ion current at different longitudinal positions in two flames,, $Re = 10^4$, $r/D = 0.5$; equivalence ratios (A) 2.62, (B) 10.4

Figure 21 Cross correlation between ion probe signals in jet flame, $r/D = 0.5$, fixed probe at $x/D = 4$. Probe separation δx; (A) 5mm, (B) 15mm, (C) 30mm, (D) 50mm, (E) 80mm.

...

LIST OF FIGURES continued ....

Figure 22 Simultaneous fluctuating temperature measurements in jet flame, r = 0.63 D, axially separated probes.

Figure 23 Simultaneous fluctuating temperature measurements in jet flame, r = 0.71D.

Figure 24 Cross-correlations between temperature fluctuations at x = 4 D, r = 0.63 D, and fluctuations at different longitudinal separations (corresponding to data in Fig. 22).

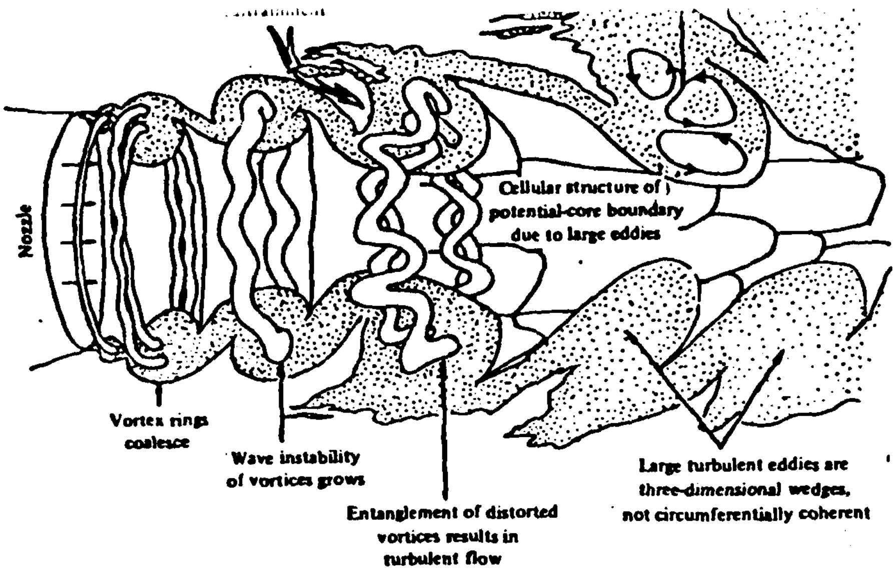


FIG. 1

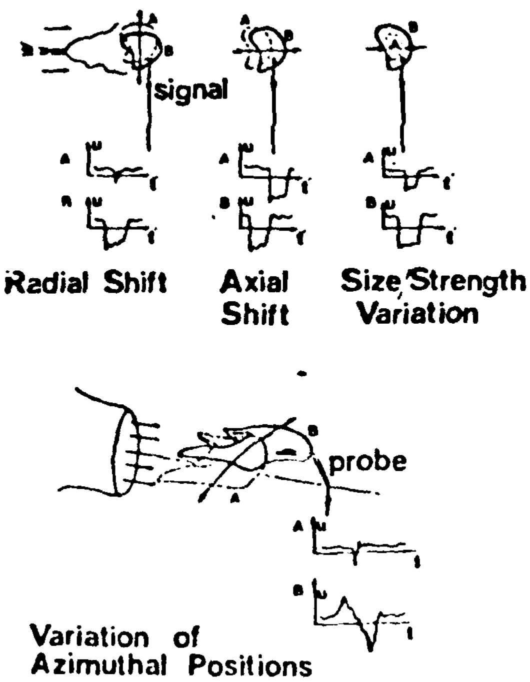


FIG. 2

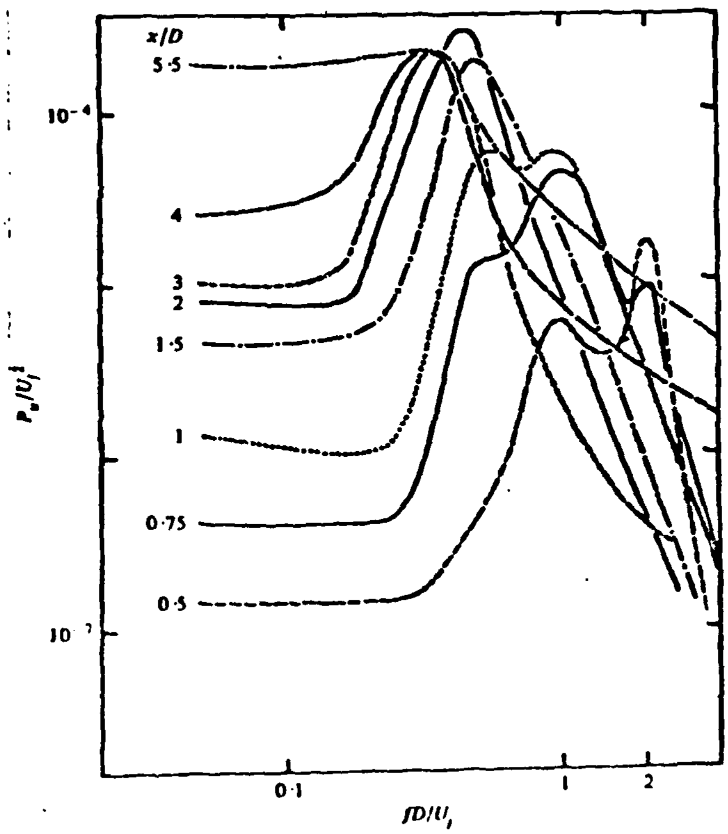


FIG. 3

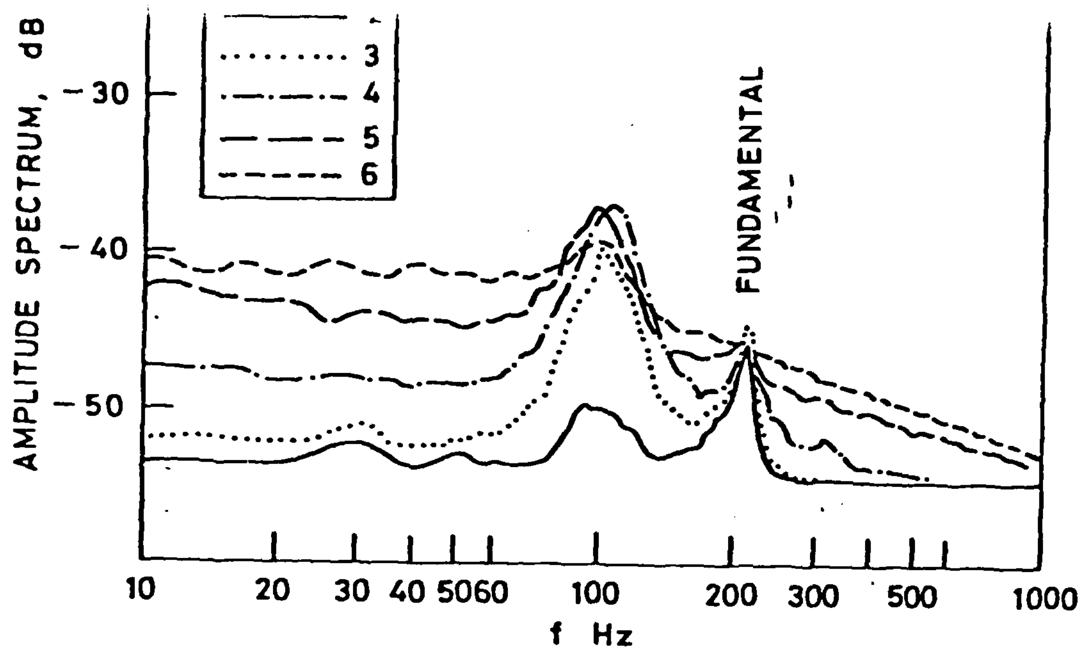


FIGURE 4

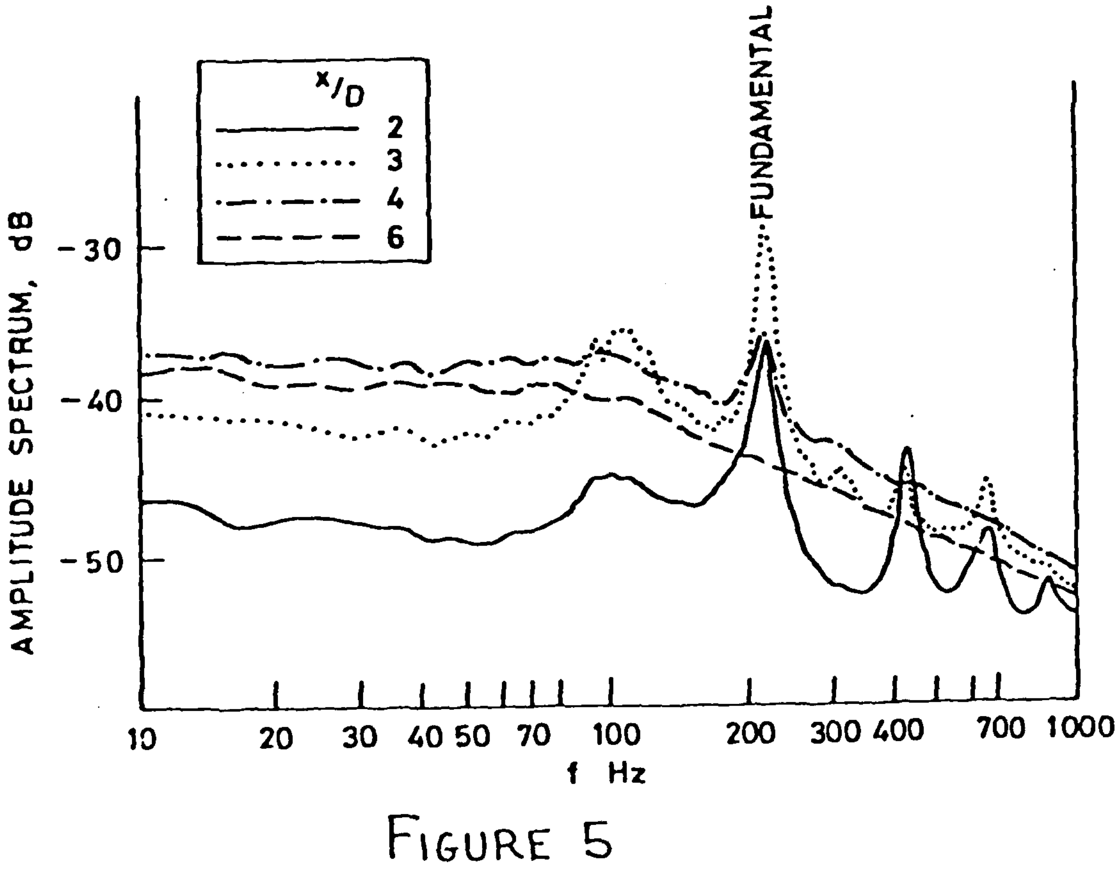


FIGURE 5

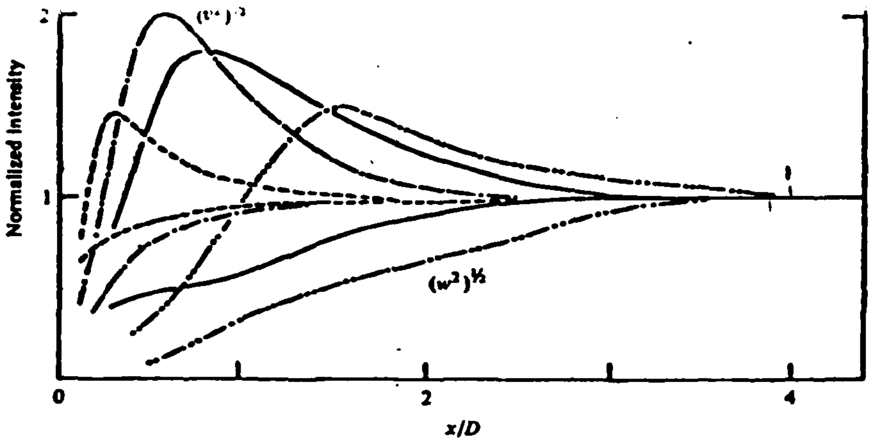

Normalized Intensity
$(w^2)^{1/2}$
x/D
0
2
4
1
2

FIG. 6

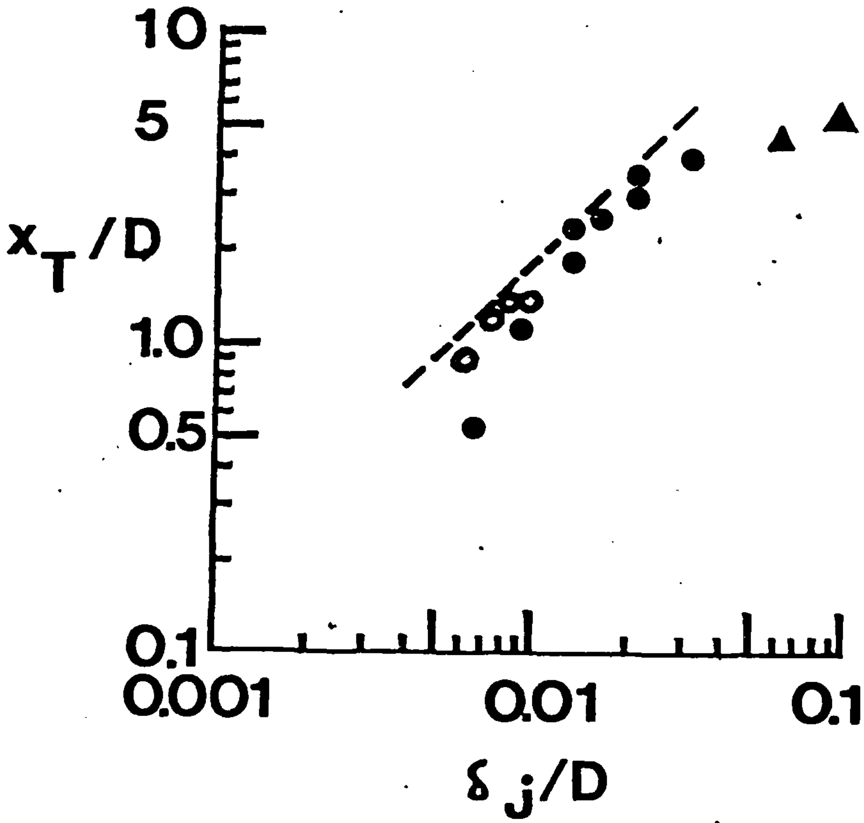
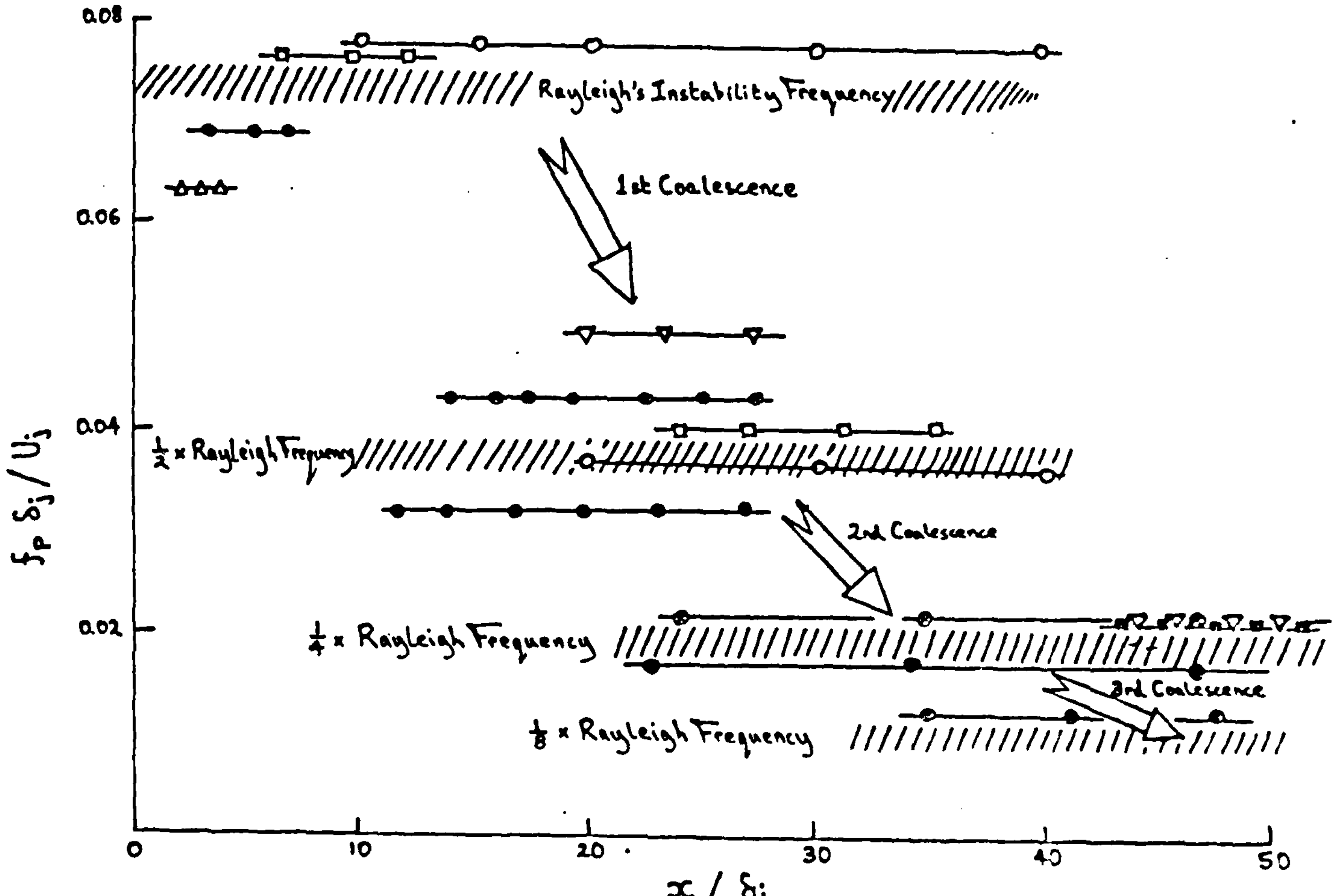

10
5
1.0
0.5
0.1
x_T/D
0.001
0.01
0.1
δ_j/D

FIG. 7



0.08
0.06
0.04
0.02
$f_p \delta_j / U_j$
0
10
20
30
40
50
x / δ_j
Rayleigh's Instability Frequency
1st Coalescence
$\frac{1}{2}$ x Rayleigh Frequency
2nd Coalescence
$\frac{1}{4}$ x Rayleigh Frequency
3rd Coalescence
$\frac{1}{8}$ x Rayleigh Frequency

FIGURE 8

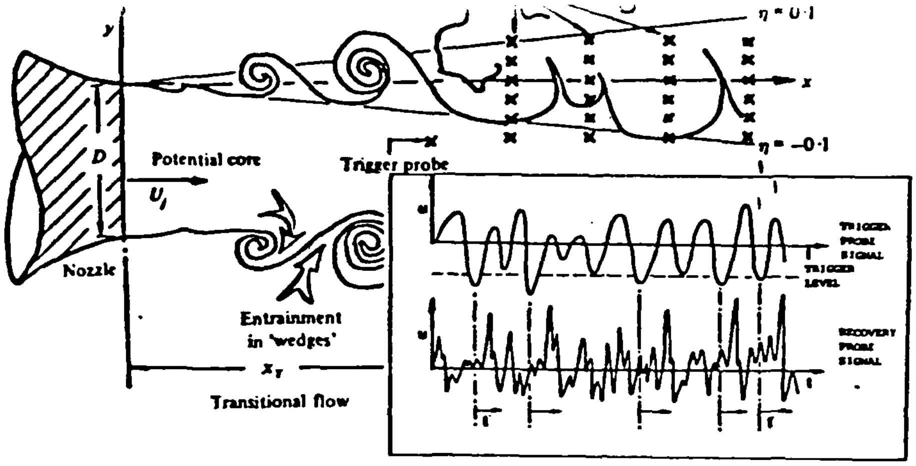


FIG. 9

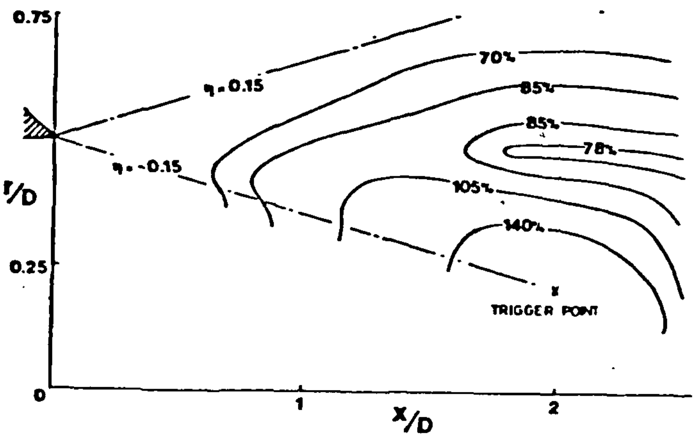


FIG. 10

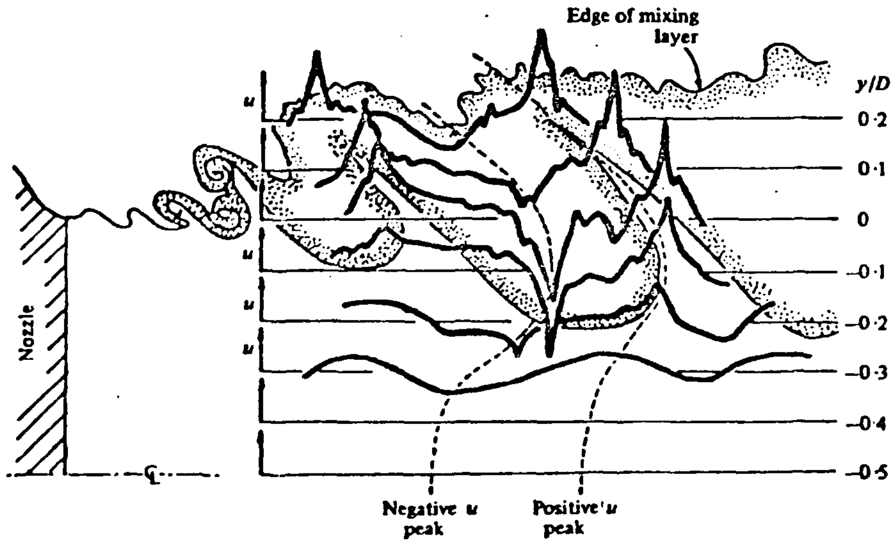


FIG. 11

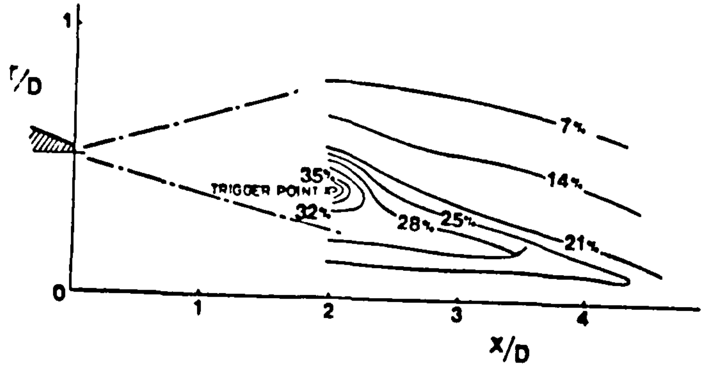


FIG. 12

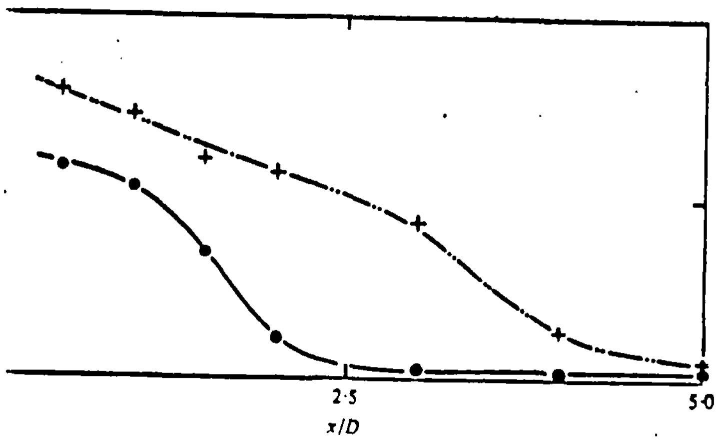


FIG. 13

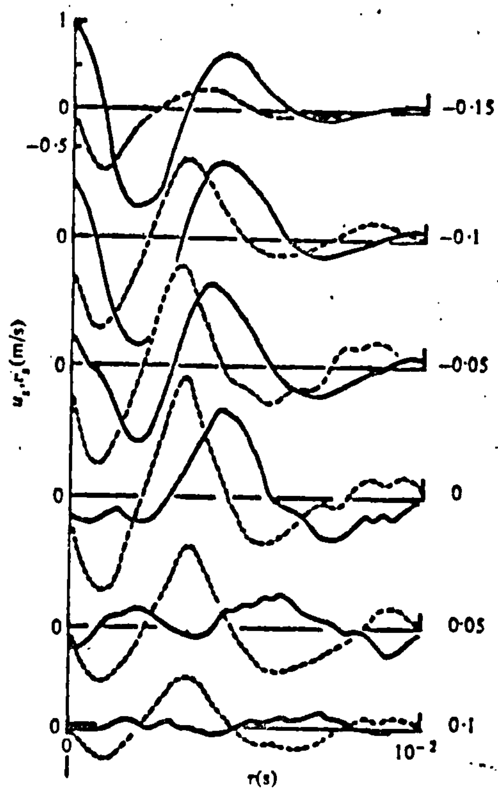


FIG. 14

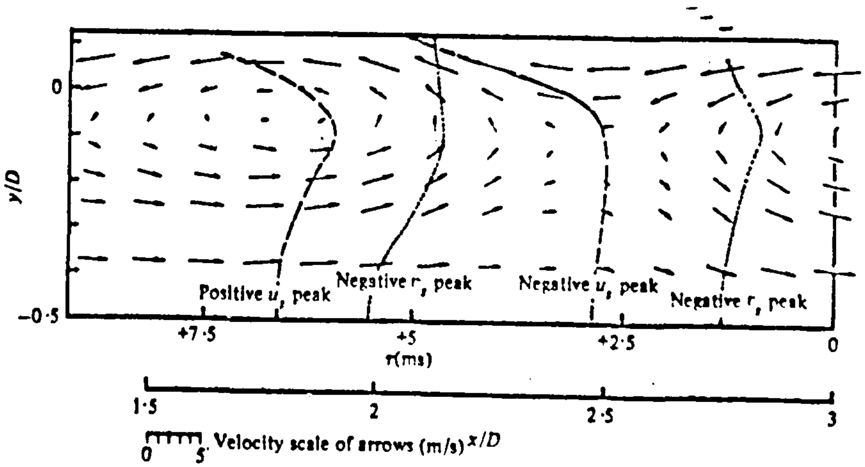


FIG. 15

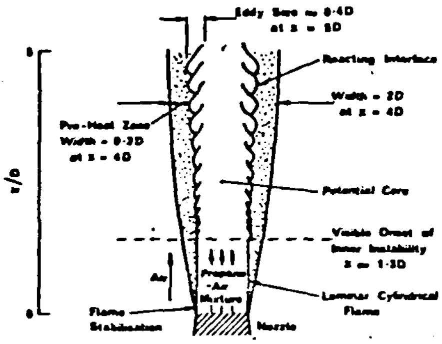


FIG. 16

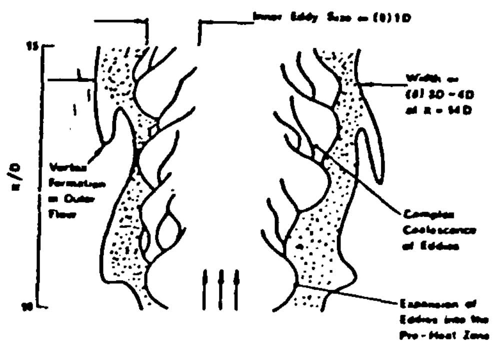


FIG. 17

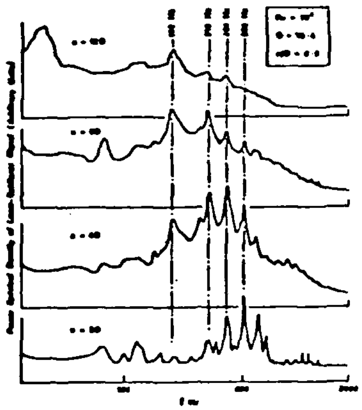


FIG. 18

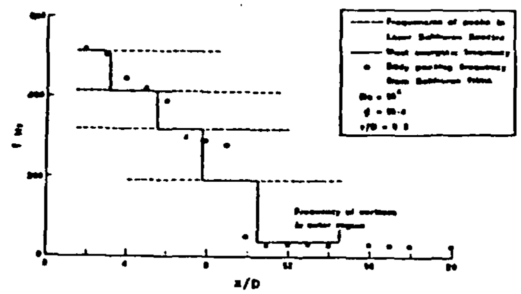
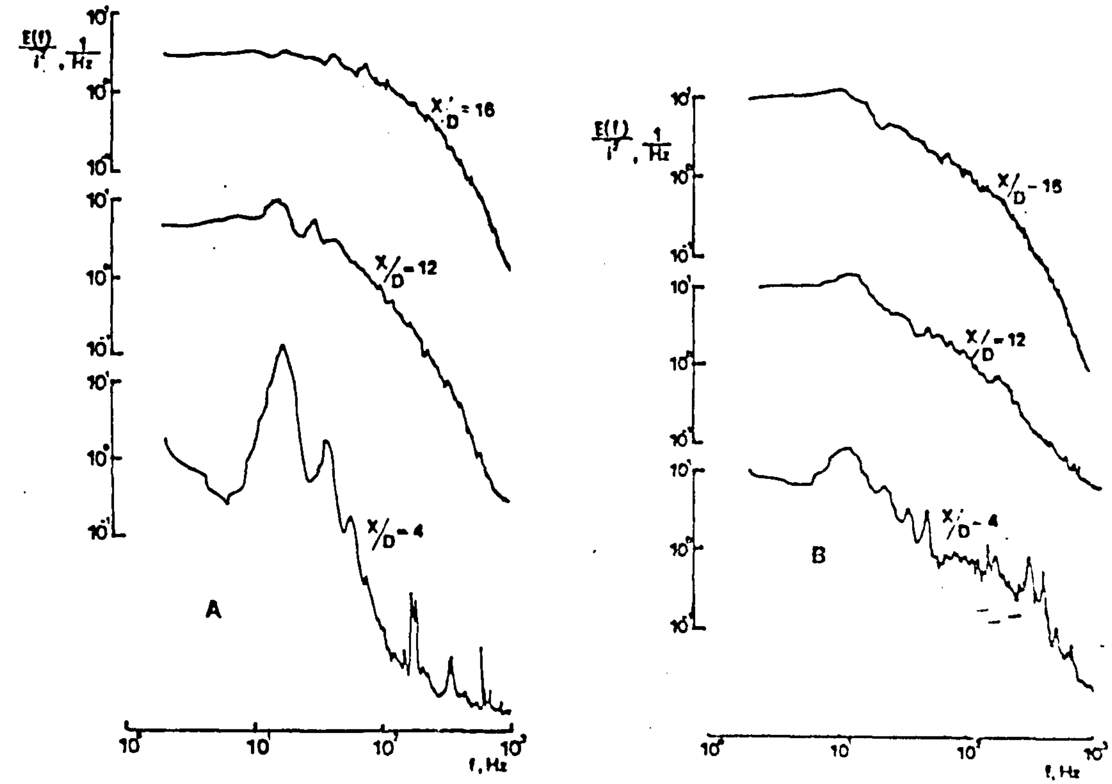
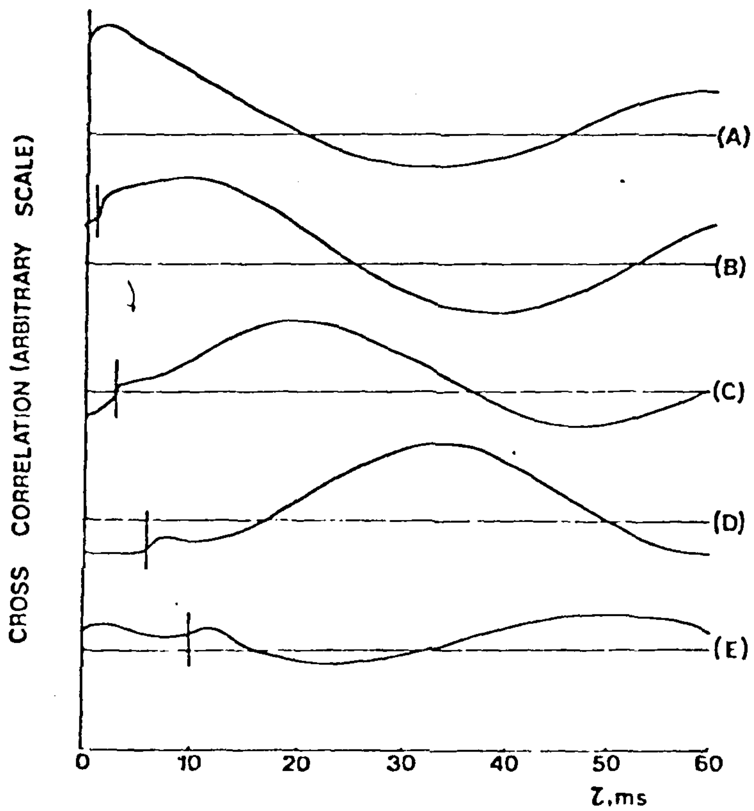


FIG. 19

FIG. 20

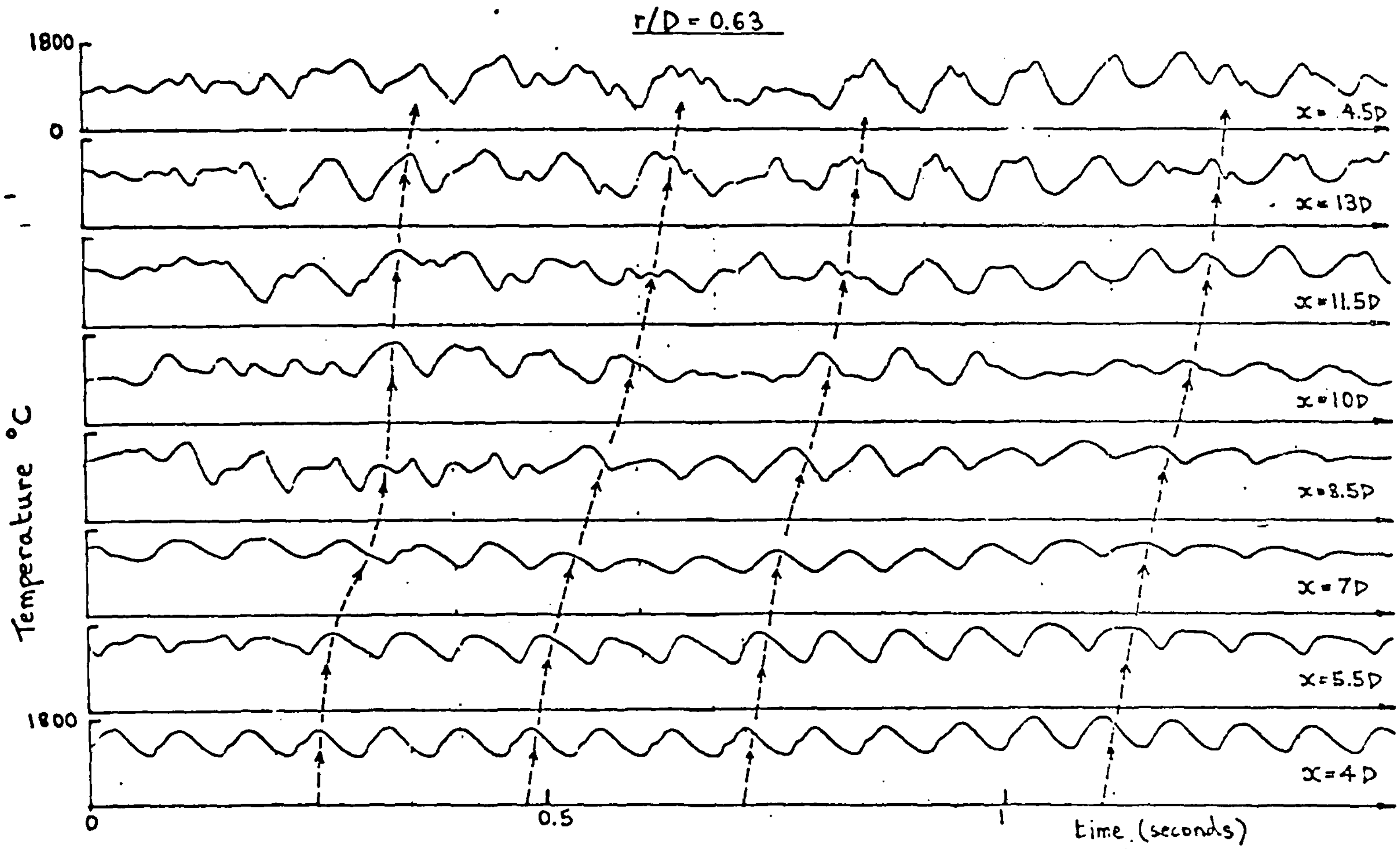




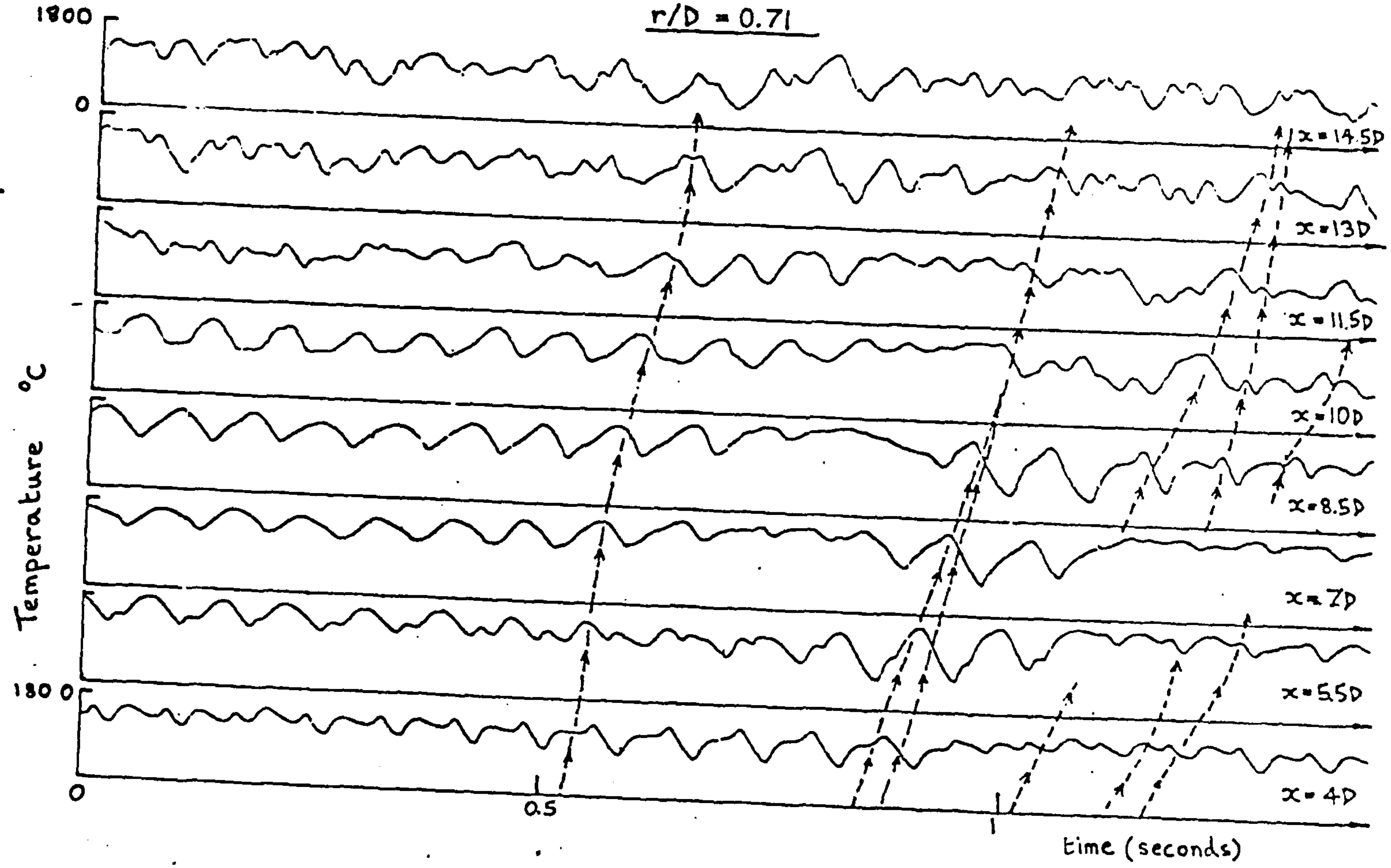
CROSS CORRELATION (ARBITRARY SCALE)
(A)
(B)
(C)
(D)
(E)
0
10
20
30
40
50
60
τ, ms

FIG. 21

FIGURE 22


r/D = 0.63
1800
0
1800
Temperature °C
x = 4.5D
x = 13D
x = 11.5D
x = 10D
x = 8.5D
x = 7D
x = 5.5D
x = 4D
0
0.5
1
time (seconds)

r/D = 0.71



1800
0
180 0
0
Temperature °C
0.5
1
time (seconds)
x = 14.5D
x = 13D
x = 11.5D
x = 10D
x = 8.5D
x = 7D
x = 5.5D
x = 4D

[...]G.23

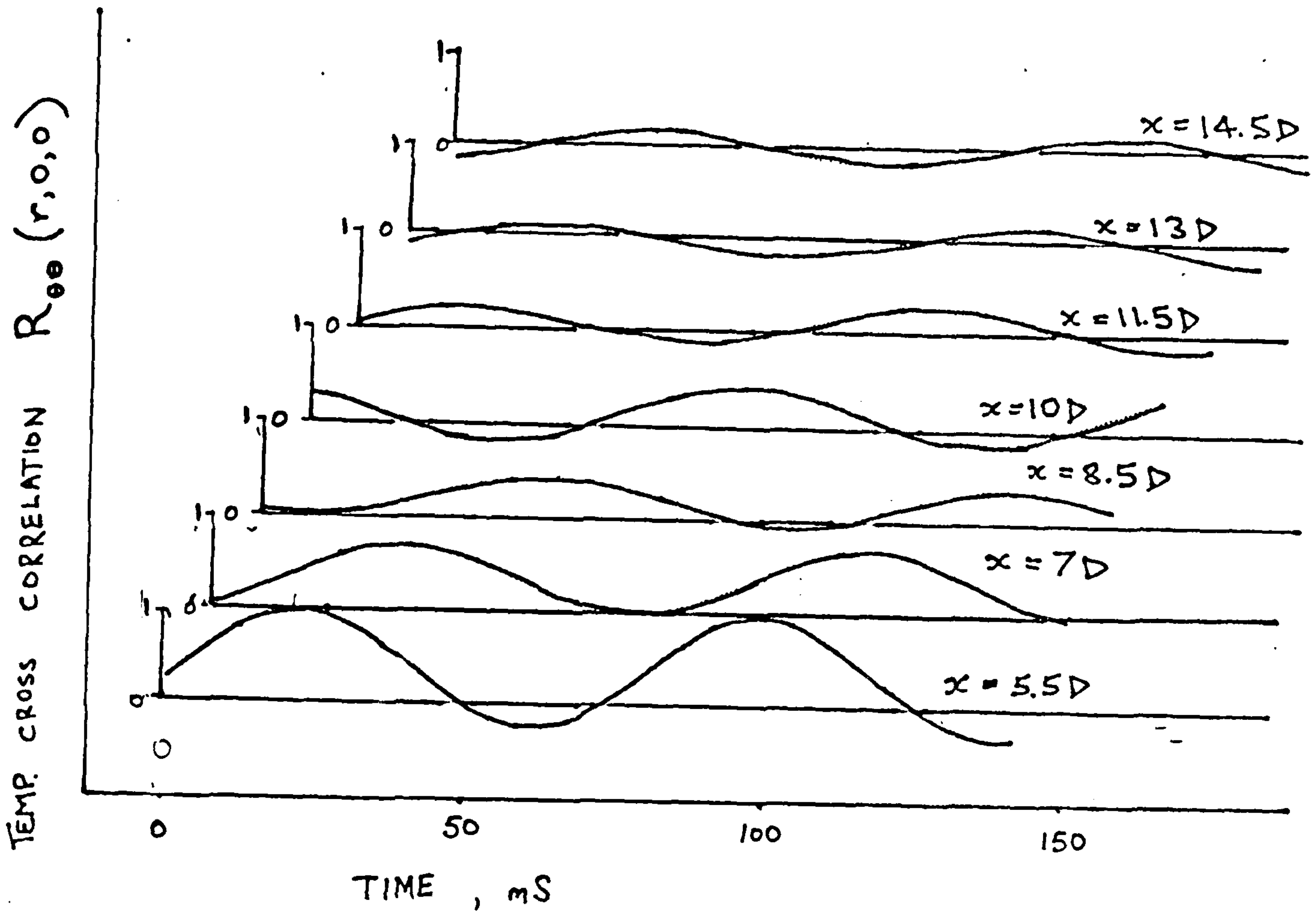

TEMP. CROSS CORRELATION $R_{\theta\theta}(r,0,0)$
x = 14.5D
x = 13D
x = 11.5D
x = 10D
x = 8.5D
x = 7D
x = 5.5D
0
50
100
150
TIME , mS

FIG. 24

DAT
FILM